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Review

Virtual and remote labs in control education: A survey

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ABSTRACT

Virtual and remote labs have been around for almost twenty years and while they have been constantly gaining popularity since their appearance, there are still many people in the control education community who either do not know many details about them or do not know them at all. What are their benefits? Which examples of virtual and remote labs for control education can be found in the Internet and how spread and popular are they? What are the current trends and issues in the implementation and deployment of these tools? And the future ones? These and others are some of the questions we answer in this paper, trying to bring the attention of the control education community to these tools which, we believe, are meant to have an increasing importance and relevance for the 21st century students.

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1. Introduction

Automatic control is mainly based on two streams of thought (Kheir et al., 1996): one stream is based in practical experience while the other stream is based in theory and mathematics. Nowadays, control engineers need to have both a deep understanding of the mathematics behind the concepts in the automatic control field and a wide experience implementing these theoretical solutions in real problems and plants. The stream based in practical experience relies on the idea that *something* needs to be controlled and so, the control systems engineering curricula must be hands-on and practice-based. This has been the traditional vision of engineering until one hundred years ago, when the second stream, based in theory and mathematics, started to gain importance (Froyd, Wankat, & Smith, 2012). This one, relies on abstract concepts such as the four identified by Kheir et al. (1996) as the major ones on control systems: *dynamic system, stability, feedback* and *dynamic compensation*, which are best modeled mathematically. As a consequence, enabling a balance between excessive theoretical proofs and emphasis on physical intuition is a major challenge in control education. In this sense, lab experimentation plays a key role to connect theory and practice. Among others, control labs fulfill the following goals (Antsaklis et al., 1998):

- Demonstrating/validating/motivating analytic concepts.
- Introducing real world control/modeling issues, such as saturation, noise, sensor/actuator dynamics, uncertainty, etc.
- Providing facility with instrumentation and measurement tools.
- Exposing students to broader design issues from problem specification to hardware implementation and economic considerations.
- Exposing students to professional practice that includes maintaining engineering notebooks and report writing.
- Team learning and problem solving.
- Comparing theoretical results with real world results, thus validating the theory.

Traditional hands-on labs involve high costs associated with equipment, space, and maintenance staff (Gomes, 2009). A line of research, which has been growing for the last twenty years, looks for reducing lab costs by taking advantage of the Internet, i.e., by substituting traditional labs with online labs.

To characterize the different modalities of experimentation environments and thus provide a precise definition of online labs, two criteria were proposed in previous work (Dormido, 2004):

1. According to the way resources are accessed for experimental purposes, environments can be *local* or *remote*.
2. According to the physical nature of the lab, environments can be *real* or *simulated plants*.

By combining those criteria, there can be the following types of experimentation environments, depicted in Table 1:

1. *Local access-real resource*. This combination represents traditional *hands-on labs*, where the student is in front of a computer connected to the real plant.
2. *Local access-simulated resource*. The whole environment is software and the experimentation interface works on a simulated, virtual and physically non-existent resource, which together with the interface is part of the computer.

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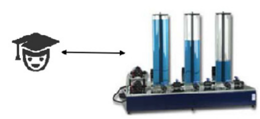
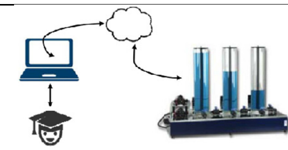
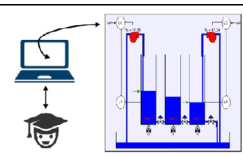
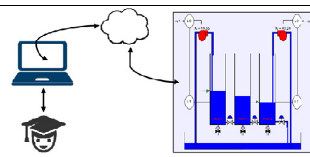
Table 1
Types of experimentation environments.

	Local access	Remote access
Real resource	 Hands-on lab	 Remote lab
Simulated res.	 *Local* virtual lab	 Virtual lab

3. *Remote access-real resource*. Real plant equipment is accessed through the Internet. The user remotely operates and controls a real plant through an experimentation interface. This approach is named *remote lab*.
4. *Remote access-simulated resource*. This form of experimentation is similar to the one above, but replacing the physical system with a mathematical model. The student operates with the experimentation interface on a virtual system reached through the Internet. As it is a simulated process, it can be instantiated to serve anyone who asks for it. This is what is usually known as *virtual lab*. In comparison with local simulated resources, virtual labs allow: (i) a decoupling of the model (which can run on the server) and the view (which runs on the client), which supports the immediate introduction of control experiences with unknown time-varying delays, and (ii) online collaborative work.

The importance and use of *Virtual and Remote Labs* (VRLs) has been growing over the years (Heradio et al., 2016; de la Torre, Sanchez, & Dormido, 2016) as the technology has progressed and some of their major concerns have been solved. From the initial conception of VRLs, one of these concerns has been assessing whether VRLs were able to provide learning outcomes comparable to traditional hands-on labs. As we will see, most empirical studies have shown that VRLs and hands-on labs are equally effective (Brinson, 2015). Moreover, VRLs provide additional advantages as the following ones (Gravier, Fayolle, Bayard, Ates, & Lardon, 2008):

1. *Availability*: VRLs can be used from anywhere at anytime, thus they support students geographically scattered, who besides are conditioned to different time zones.
2. *Observability*: lab sessions can be watched by many people or even recorded.
3. *Accessibility*: labs can be accessed by handicapped people.
4. *Safety*: VRLs can be a better alternative to hands-on labs for dangerous experimentation.

While there are a fairly amount of works addressing the assessment of VRLs and many more about particular implementations and general architectures for them, there are few papers that study their history and evolution. This survey tries to overview the past, present and future of VRLs in control education. To do so, it is structured as follows. Section 2 provides a catalog of VRLs for control engineering currently available on the Internet. Section 3 outlines the most common approaches to develop VRLs and deploy them through the Internet. Section 4 reviews empirical studies on assessing the VRLs educational effectiveness compared to hands-on labs. Section 5 tries to foresee the future trends in the area. Finally, Section 6 summarizes the conclusions of our work.

2. Online labs for control education

In 1998, the National Science Foundation and the Control Systems Society Workshop on “New Directions in Control Engineering Education”, held at the University of Illinois at Urbana-Champaign, produced, as one of its outcomes, a report summarizing the major conclusions and recommendations that emerged from the workshop (Antsaklis et al., 1998). A shorter version of such report was published in the IEEE Control Systems Magazine (Antsaklis et al., 1999). In both documents, the authors recognize the potential value of remote labs and state that *“students can gain practical laboratory experience over the Internet”* and that *“remote or eyes-on laboratories can serve a valuable purpose in several ways”*, particularly *“as a way to maximize the use of expensive laboratory equipment”* and *“as a way to provide laboratory exposure when hands-on labs are not possible”*. However, they identify a problem on how WWW-based control systems educational materials could be found in the Internet back on those days, arguing that websites were scattered and their material lacked documentation and quality evaluation. Thus, they stand up for a cooperative effort among professional control organizations to develop and coordinate WWW-based tools for control education. Among other recommendations, they come up with this one:

“Improve information exchange by creating a centralized Internet repository for educational materials. These materials should include tutorials, exercises, case studies, examples, and histories, as well as laboratory exercises, software, manuals, etc.”

The documents then clarify that *“this repository can also contain links to remote sites, especially sites that provide virtual laboratories for control”*. While the authors explicitly mention virtual labs and omit remote labs, this must be understood from the perspective of what they considered doable at the time. Back in 1998 it was difficult to think about the possibility of sharing remote laboratories and so, writing down an explicit recommendation encouraging control organizations to create, deploy and share remote labs would probably have been too daring. Still, they wrote a recommendation on how to promote the appearance of WWW-based tools for control education, whether these tools were exercises, tutorials, virtual labs or remote labs:

“Promote the development of a set of standards for Internet based control systems materials and identify pricing mechanisms to provide financial compensation to Internet laboratory providers and educational materials providers.”

Unfortunately, eighteen years later, we can not say that these particular recommendations have been addressed by the control organizations and, therefore, virtual and remote labs are not of-

fered nor stored in any public repository. As a result, most of the VRLs on control systems presented in works published in journals and conferences cannot be easily (or at all) found on the Internet. Moreover, as a result of the lack of support from the professional control organizations, remote labs are usually not openly accessible.

Table 2 summarizes the VRLs on control systems the authors could find after an exhaustive search on both the Internet and the literature. In order to avoid useless information, we decided to include only those labs that were operating on April 2016 which, despite the high number of works published in recent years presenting remote labs, were not so many. This fact reveals an important issue on remote labs: it is not only expensive their development, but also their maintenance. An institution may have funding for developing some VRLs but sooner or later, when the funding stops, the institution becomes unable to support the lab maintenance. As we will see in Section 5.1, great efforts are being made towards the cross-institutional sharing of VRLs in order to divide the VRL development and maintenance costs.

3. Implementation and deployment of VRLs

For years, the multidisciplinary effort required for developing and building virtual and, especially, remote labs combined with the lack of tools for supporting their creation, has made that building one single VRL for a complex control system experience supposed a huge effort in the past. For example, Sanchez's Ph.D. research topic addressed the sole creation of just one virtual and remote lab for controlling an inverted pendulum (Sanchez Moreno, 2001). As time passed and the technology advanced, creating VRLs stopped being such a painful ad-hoc process in which no reusability could be obtained, and allowing teachers to focus more in the pedagogical aspects of the VRLs rather than on the technical parts of building them (Esquembre, 2015).

Sections 3.1 and 3.2 discuss the main architectural and technological issues regarding the creation of VRLs nowadays. Thanks to tools that assist teachers on creating the VRLs, this has stopped being a titanic task. Afterwards, Section 3.3 summarizes how VRLs are deployed in educational environments which, until more recently has been (an to some extent, still is) a difficult issue that has also been tackled in some recent PhD research topics (Sancristobal, 2010; de la Torre, 2013).

3.1. Virtual labs

Virtual Labs (VLs) can be implemented as *desktop programs* (running natively on the user's operating system) or *web-based applications* (running on the user's web browser). Compared to web-based applications, desktop programs have the following drawbacks:

- They are less portable: desktop applications are bounded to a particular platform, e.g. an operating system, the Java Virtual Machine, the .NET Common Language Runtime, etc.
- They are less secure: desktop applications usually require complete-access privileges to be installed, they have full access to the user's hard disk, they can open unrestricted connections to the outside world, etc.

As a result, most VLs are implemented as web-based applications (Garcia-Zubia, Orduña, Lopez-de Ipiña, & Alves, 2009).

In general, once the VL is running on the user's browser, it does not require to establish new connections to the exterior. Nevertheless, the VL architecture may become more complex in some exceptional cases:

- If the simulation has an excessive computational cost for the student's computer (or tablet, mobile phone, etc.) then a client-server architecture can be used. For instance, Saenz, Esquembre, Garcia, de la Torre, and Dormido (2015) propose running a light graphical interface on the client, which controls the computations performed on the server.
- To enable students geographically scattered working collaboratively on the same VL, de la Torre et al. (2013) propose the creation of peer-to-peer (P2P) networks among students' browsers. In each network, the teacher or one of the students plays the session director role, being responsible for starting, monitoring and closing the collaborative session. The remaining participants are only allowed to see in real-time what the director is doing in the shared simulation, unless the director momentarily cedes the VL control to other participant. The P2P network is centralized around the session director, hence all simulation instances running on the participants' browsers are synchronized according to the director's instance. This way, collisions of events, which may cause unwanted and incoherent results, are avoided.

Programming a VL from scratch requires a considerable effort and involves repetitive work. For instance, a basic requirement for VLs is being interactive and dynamic: any change in the simulation parameters should be immediately reflected in the graphical user interface (Sanchez, Morilla, Dormido, Aranda, & Ruiperez, 2002). Thus, students can visualize on the fly how the model behavior evolves according to the values of the interactive parameters. Programming that interactivity is not trivial and it has to be done for every VL. To avoid that redundant work and increase the productivity in VL development, there are authoring tools, such as EjsS[1], which offers high level graphical interfaces to create computer simulations. Thanks to EjsS, users without programming knowledge can specify the mathematical model of a VL, and how the VL should be visualized. Then, EjsS automatically generates the code that implements the specified lab.

In order to support a realistic user experience, VLs should provide rich media, such as 3D-graphics, video, audio, etc. Unfortunately, these features have not been supported by HTML for a long time. To overcome the HTML limitations, the most common choice to develop VLs has been Java applets. Nowadays, as Java applets are being progressively unsupported by most web browsers, and new JavaScript standards (HTML5, WebGL, etc.) already provide rich media, the current trend is moving to JavaScript. The downside of this shift in the technology is that while there are plenty of Java libraries for control systems engineering that ease the creation of virtual labs in this field (such as, for example, Prof. Michael Thomas Flanagan's,[2] which offers classes for things like building open and closed loops, first and second order processes or PID controllers), these do not yet exist in JavaScript.

3.2. Remote labs

Since *Remote Labs* (RLs) teleoperate real equipment, they are generally more complex and expensive than VLs. To tackle such complexity, RLs follow a client-server architecture.

The RL client-side is usually a web-based application that interacts with the server-side to tele-control the actual setup and visualize information from the lab (video streaming, sensor data, etc.).

VLs and the client-side of RLs share many common features (after all, they are *Rich Internet Applications* for lab experimention), and thus both are usually implemented with the same technology (i.e., Java in the past, and JavaScript at the moment). Furthermore, some approaches take advantage of these similarities to blender virtual and remote labs by superimposing a graphical representation of the VL behavior over the image provided by the webcam

[1] http://www.um.es/fem/EjsWiki/pmwiki.php.

[2] http://www.ee.ucl.ac.uk/~mflanaga/java/ClassList.html#control.

Table 2
Catalog of VRLs on control systems.

Website	Lab name	URL	Type	Open?	Description
UNILabs	3 DOF Quadrotor	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control the pitch, roll and yaw in a non-linear system consisting of a frame with 4 propellers mounted on a 3 DOF pivot joint
	Ball and beam	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control the position of the ball and move it to the desired position along the beam
	Ball and plate	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control the position of the ball by manipulating the slope of the plate in two perpendicular directions
	Ball and hoop	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control the oscillations of the ball in the hoop, similar to the dynamics of a liquid inside a cylindrical container
	Direct current motor	http://unilabs.dia.uned.es/course/view.php?id=24	V&R	Yes	Position and velocity control on a first order system
	Flexible link	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control the position of the tip minimizing the vibrations that appear due the elasticity of the link
	Three coupled tanks	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Level control on a MIMO system with slow dynamics
	Four coupled tanks	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Multivariable control to regulate the level of one tank
	Inverted pendulum	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control a nonlinear, unstable, non minimum-phase, and underactuated system
	Furuta's pendulum	http://unilabs.dia.uned.es/blog/index.php?entryid=3	V&R	No	Control an unstable device that exhibits non minimum phase behavior
	Heat-flow	http://unilabs.dia.uned.es/course/view.php?id=24	V&R	Yes	Temperature control on a second order system with delays
	Two coupled electric drives	http://unilabs.dia.uned.es/course/view.php?id=24	V&R	Yes	Tension and velocity control of a 2x2 MIMO system
iLabCentral	Dynamic Signal Analyzer	http://ilabcentral.org/2.php	R	No	Frequency domain measurements on electronic circuits and control systems
	Inverted Pendulum	http://ilabcentral.org/9.php	R	No	Derive and tweak control laws in order to balance a pole
LRA	4-Tanks Model	http://lra.unileon.es/content/physicalsystems/4tankmodel	R	No	A multivariable laboratory process with an adjustable zero
	4-Variables Model	http://lra.unileon.es/content/physicalsystems/4variablesmodel	R	No	Intelligent industrial instrumentation for measurement and control of flow, level, pressure and temperature to test control strategies
	Industrial Model	http://lra.unileon.es/content/physicalsystems/industrialmodel	R	No	This pilot plant models the most common control loops in industry with the aim to be a valuable tool for their study
	Robot	http://lra.unileon.es/content/physicalsystems/robotic_cell	R	No	A six degrees of freedom robot for defining trajectories
	Ethernet and Profibus networks of PLCs	http://lra.unileon.es/content/physicalsystems/plcs	R	No	Configuration and programming of PLCs through the Internet
	Remote Control and Motor Monitoring	http://lra.unileon.es/content/physicalsystems/variable_speed	R	No	Driver controlled by a PLC through a Profibus Network managed through an Ethernet network
	Electropneumatic Cell for Classification	http://lra.unileon.es/content/physicalsystems/electropneumaticpanel	R	No	This system simulates an assembly line
	Feedback MS-150 equipment	http://lra.unileon.es/content/physicalsystems/feedback	V&R	No	Interactive simulation and remote access of the Feedback MS-150 equipment for identification, position and velocity control and PID tunning
Rex-controls	PID control lab	https://www.rexcontrols.com/pid-control-lab-3-1	V	Yes	PID optimization based on: gain and phase margins, sensitivity functions shaping, loop bandwidth, and Nyquist plot shaping
	PIDMA	https://www.rexcontrols.com/pidat-demo	V	Yes	Demonstrates functions of a PID controller with pulse autotuner
	PIDAT	https://www.rexcontrols.com/pidat-demo	V	Yes	Demonstrates functions of a PID controller with relay autotuner
	PSMPC	https://www.rexcontrols.com/psmpc-demo	V	Yes	Pulse step predictive controller for difficult to control processes
	ZV4IS	https://www.rexcontrols.com/zv4is-demo-2	V	Yes	FIR band-stop frequency filter
	SC2FA	https://www.rexcontrols.com/sc2fa-demo	V	Yes	Self tuning controller for oscillating systems
	SMHCCA	https://www.rexcontrols.com/smhcca-demo	V	Yes	Heating-cooling temperature sliding mode controller
	Smith predictor	https://www.rexcontrols.com/smith-predictor	V	Yes	Structure of Smith predictor controller for dead-time dominant processes
	PWM	https://www.rexcontrols.com/pwm-demo	V	Yes	Pulse width modulation principle in PID control applications
	Bumpless transfer	hhttps://www.rexcontrols.com/bumpless-transfer	V	Yes	Structure for bumpless switching of PID controller parameters and automatic/manual mode
	Stepping controller	https://www.rexcontrols.com/stepping-controller	V	Yes	PID control of a servo-valve without position feedback
	Split range control	https://www.rexcontrols.com/split-range-control	V	Yes	Process PID control with two actuators
	Floating control	https://www.rexcontrols.com/floating-control	V	Yes	Floating control approach to control process with two actuators
	Center seeking control	https://www.rexcontrols.com/center-seeking-control	V	Yes	Center-seeking approach to PID control process with two actuators
Rex-controls	Cascade control	https://www.rexcontrols.com/cascade-control	V	Yes	Advanced cascade control where the wind-up effect of both PID controllers is solved as well as bumpless transfer between manual/automatic modes
LabShare	Coupled tanks	http://www.labshare.edu.au/catalogue/rigtypedetail/?id=1&version=2	R	No	Test the response of a coupled tank system and tune different kinds of controllers in real-time
GO-LAB	Segway control	http://www.golabz.eu/lab/segway-control-simulation	V	Yes	Digital control system to continuously analyze the position and orientation of a segway and act on its wheels to keep it standing
VLAB	Heat exchanger	http://ial-coep.vlabs.ac.in/Expt6/Theory.html	V	Yes	Tune a PID controller for heat exchanger using DCS

of the actual lab (Andujar, Mejias, & Marquez, 2011; Rodriguez-Gil, Orduña, Garcia-Zubia, Angulo, & Lopez-de Ipiña, 2014; de la Torre, Guinaldo, Heradio, & Dormido, 2015a). This allows a visual comparison of the theoretical response of the plant with the real response. Such approaches are commonly referred as VRLs with *augmented-reality* (Andujar et al., 2011).

Traditionally, the RL server-side has been implemented as LabView or Matlab/Simulink programs running on PC computers (Ertugrul, 2000; Hercog, Gergic, Uran, & Jezernik, 2007; Stefanovic, Cvijetkovic, Matijevic, & Simic, 2011). This approach is quite expensive, since it requires (i) dedicating a PC computer for each lab, and (ii) paying the software licenses of LabView or Matlab/Simulink. Fortunately, the hardware scenario is changing quickly, and nowadays it is possible to substitute the PC computer with much more affordable options, such as BeagleBone, Arduino, or Raspberry Pi. For example, Saenz et al. (2015) describe the development of low-cost VRLs on control engineering (two coupled electric drives, a DC motor, and a heat flow system) using a BeagleBone Black board which is directly connected through a Node.js server with the client-side implemented with EjsS. This way, the software costs disappear as LabView and Matlab/Simulink are replaced by Node.js, which (as well as EjsS) is free. Similarly, Bermudez-Ortega, Besada-Portas, Lopez-Orozco, Bonache-Seco, and de la Cruz (2015) also present a solution for low-cost remote labs using Raspberry Pi and Node.js to apply PID control to a vertical mono-rotor plant.

3.3. VRL deployment

Once a VRL is built, it must be made available to its users. In the educational context, that means enriching the VRL with the following features:

- *Lab scheduling*. Typically, a RL can be used by just one student at a time. Hence, a scheduling system is required to manage the lab availability. Such system may be a booking system, a queue, or a combination of both (Lowe, 2013).
- *User's authentication*. Most times, the access to experimental apparatus must be restricted to a given group of students.
- *Social context*. There is empirical evidence of the positive effects that collaborative work have on online experimentation (Jara, Candelas, Torres, Dormido, & Esquembre, 2012; van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005; Shyr, 2012; de la Torre et al., 2013). Hence, it is desirable to support the interaction among participants (students and teachers) by means of both synchronous (e. g., chat, video-conference...) and asynchronous (e. g., whiteboards, forums, mailing list...) collaboration tools.
- *Distributing all the convenient resources for the experiment*. Attached to the VRL, it is often useful delivering a description of the phenomena under study, the task protocol that students must follow to achieve the goals of the lab activities, etc.

At the beginning, ad-hoc authentication systems were created to manage the user's access to particular RLs. Nowadays, the following more general and powerful solutions are preferred:

- *Integrating VRLs into Learning Management Systems (LMSs)*. As the aforementioned features (user authentication, social context, etc.) are supported by most LMSs, a common approach to distribute VRLs is embedding them into LMSs. For instance, Restivo, Mendes, Lopes, Silva, and Chouzal (2009), Barrios et al. (2013), Heradio, de la Torre, Sanchez, and Dormido (2014), de la Torre et al. (2015a), de la Torre, Heradio, and Sanchez (2015b) propose integrating VRLs into Moodle, Daponte, Grimaldi, and Rapuano (2010) into LADIRE, and Sancristobal-Ruiz et al. (2014) offers a general approach in which VRLs can be integrated into many LMSs.
- *Deploying RLs into Remote Laboratory Management Systems (RLMSs)*. RMLSs are platforms specifically designed for RL deployment. Probably, the most relevant is iLab (Harward et al., 2008), which started at the Massachusetts Institute of Technology in 1998 and remains in use and development (Colbran & Schulz, 2015). It is also worth mentioning the RLMSs WebLab-Deusto (Kaluz, na, Garcia-Zubia, Fikar, & Cirka, 2013) and LabShare (Lowe et al., 2012).

4. Assessing the educational value of VRLs

VRLs are essential to support experimentation in online and blended learning, which has become extremely popular for the last years. The annual reports by the Babson Survey Research Group are helpful to get an overall picture of the importance that online education is gaining. These reports have been published since 2002 to account for the state of online learning in U.S. higher education. In particular, the last one (Allen & Seaman, 2014) takes into account responses from more than 2800 colleges and universities, providing the following figures:

- In 2012, 7.1 million of students took at least one online course, which means the 33.5% of the total higher education students. Moreover, 95% of the academic leaders think that it is “Likely” or “Very Likely” that most higher education students will be taking at least one online course by 2020.
- The percentage of academic leaders who claim that online learning is critical to institutional long-term strategy has increased from 48.8% in 2002 to 70.8% in 2014. Likewise, the percentage of academic leaders thinking that the learning outcomes provided by online education are comparable to those provided by face-to-face instruction has grown from 57% in 2003 to 74% in 2014.

Other recent reports have also stated the importance and relevance VRLs can have in today's education. For example, the NMC Horizon Report, in its 2013 K-12 Edition (Johnson et al., 2013), identifies VRLs as one of the main challenges that should be considered and addressed in education. In particular, it predicts that the use of this technology would become mainstream in schools in about five years since the report's date of publication, assuming the blended learning scenario will also be mainstream.

Given the relevance that online and blended learning are acquiring, and the key role that VRLs play in such modalities of education for engineering and science, a major concern since the initial conception of VRLs has been assessing whether they are able to provide learning outcomes comparable to traditional hands-on labs.

Most empirical studies have shown that VRLs enable learning results comparable to traditional hands-on labs (Gustavsson et al., 2009; Kostaras, Xenos, & Skodras, 2011; Lindsay & Good, 2005; Nedic, Machotka, & Nafalski, 2003; Nickerson, Corter, Esche, & Chassapis, 2007; Sicker, Lookabaugh, Santos, & Barnes, 2005). In this sense, the most conclusive work to date is probably Brinson's study (Brinson, 2015), where 56 articles that empirically evaluate VRLs versus hands-on labs are jointly analyzed. Figs. 1 and 2 depict the main results of Brinson's review: 35 papers show that VRLs enable higher learning outcomes than hands-on labs, 12 papers show that both VRLs and hands-on labs are pedagogically equivalent, 6 papers show better learning outcomes for hands-on labs, and 3 papers report that both types of labs have their own strengths and weaknesses (e.g., one of these 3 papers (Gorghiu, Gorghiu, Alexandrescu, & Borcea, 2009) found that the use of VRLs resulted in a higher level of conceptual understanding, motivation, and hypothesis/model confirmation, but teachers expressed concern with students not learning physical skills related to equipment handling and lack of careful observation of the real phenomena).

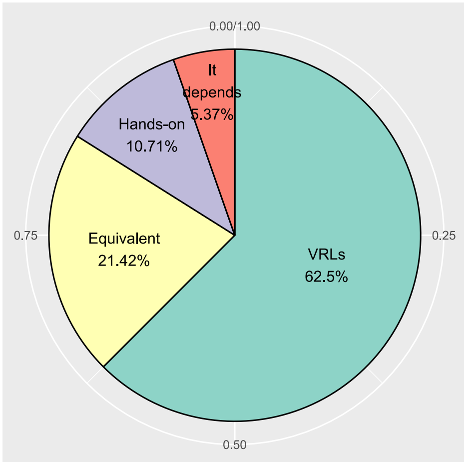


Fig. 1. Percentage of studies comparing the learning outcomes of VRLs vs hands-on labs.

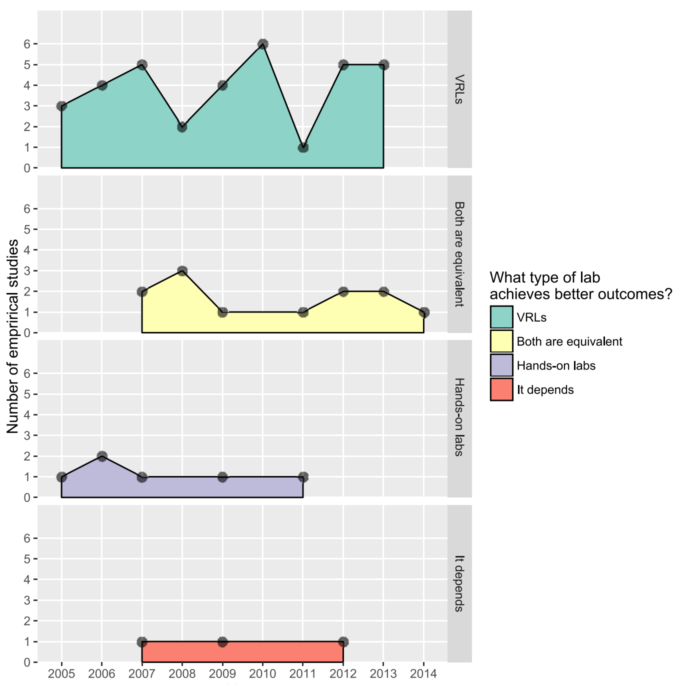


Fig. 2. Number of studies comparing the learning outcomes of VRLs vs hands-on labs along the time.

Whereas Fig. 1 shows the percentage of papers per category, Fig. 2 depicts the number of papers per year showing that the interest on assessing the VRL effectiveness has remained along the time, and that the number of studies revealing VRLs deficiencies have progressively decreased.

Other studies have focused on comparing the effectiveness of remote versus virtual labs. For instance, Stefanovic, Tadic, Nestic, and Djordjevic (2015) report an empirical evaluation for control engineering education, where students state preference of remotely-controlled labs over simulations because they provide a more realistic perception of the experiments. Other authors (de Jong, Linn, & Zacharia, 2013; Toth, Morrow, & Ludvico, 2009) claim that, when students use remote labs, they tele-operate actual physical apparatus and get real data, and hence students learn about the complexities of the real world (e.g., dealing with measurement errors whose simulation is far from trivial).

In contrast, other authors defend the particular advantages of virtual labs: (i) they support experimentation about unobservable phenomena (Chiu, DeJaegher, & Chao, 2015; Jaakkola, Nurmi, & Veermans, 2011; de Jong et al., 2013; Levy, 2013), (ii) they adapt reality and thus properties of the underlying mathematical model of the simulation can be changed to make easier the interpretation of certain phenomena (Ford & McCormack, 2000), (iii) they enable emphasizing prominent information or remove confusing details (Trundle & Bell, 2010), and (iv) they promote students' engagement into "what if" explorations where the outcomes of the virtual experiments can be immediately accessed (Hennessy et al., 2007).

In our opinion, virtual, remote and hands-on labs are not exclusive alternatives, but valuable educational resources that can be combined in one integral and complementary learning unit. Such belief is supported by experimental evidence, as the pre-post comparison study design performed by Zacharia (2007), which showed that the combination of remote and virtual experimentation enhanced students' conceptual understanding more than the use of remote experimentation alone.

Finally, instead of validating the general concept of VRL *per se*, there is a growing interest on assessing the educational effectiveness of particular VRLs. In this sense, the following research lines should be highlighted:

- *Models for evaluating VRLs in a systematic way*. For instance, Nickerson et al. (2007) propose a model to measure the impact of a given VRL in terms of: lab suitability to accomplish the learning objectives, lab support for social coordination, and lab capability to accommodate student's individual differences (e.g., to take into account the student' grade level, cognitive style, psychological development etc.)
- *Learning analytics for VRL assessment*. In the era of Big Data, learning analytics have begun to be applied to collect and analyze extensive information about the student's interaction with the VRLs (a) to assess the lab effectiveness (Wuttke, Hamann, & Henke, 2015), (b) to characterize how a given lab is used in different contexts (e.g., distinct institutions or types of institutions) (Orduña, Almeida, Lopez-de Ipiña, & Garcia-Zubia, 2014), (c) to support students' continuous evaluation (Romero, Gueaga, Garcia-Zubia, & Orduña, 2014), etc.

5. Future trends

This section presents an attempt to estimate the future trends on VRLs in general, and about their application on control systems education in particular.

5.1. Cross-institutional lab sharing

Once a VRL is deployed through the Internet, the lab usage costs are the same for people placed close to the actual apparatus, than for people living in the opposite pole of the world. This opens new opportunities for sharing experimentation resources not seen until now and, as the following points show, this particular issue is a line of work of utmost importance for the VRL community:

- The Labshare consortium is a lab sharing initiative of five Australian Technology Network Universities backed by the Australian Governments Diversity and Structural Adjustment Fund. The Labshare mission is Kostulski and Murray (2010): *"to create a nationally shared network of remote laboratories that will result in higher quality labs that support greater student flexibility and better educational outcomes, improved financial sustainability, and enhanced scalability in terms of coping with student loads"*.

- NeReLa[3] is a collaborative project co-funded by the Tempus Programme of the European Union. It is composed of thirteen partners from six countries, and its main goal is *"sharing and exchanging remote engineering experiments as open educational resources"*.
- Go-Lab[4] is another project co-funded by the European Union that is composed of eighteen organizations from twelve countries. It looks for offering a federation of VRLs for large-scale use in education (de Jong, Sotiriou, & Gillet, 2014).
- The Global Online Laboratory Consortium[5] is currently composed of eighteen universities from the five continents. Its mission is *"the creation of sharable, online experimental environments which increase the educational and scientific value of learning which may not be accessible, scalable or efficient through traditional methods"*.
- Probably, the most influential work in lab sharing has been the pioneer project iLab from the Massachusetts Institute of Technology (Harward et al., 2008), whose goal is: *"developing a distributed software toolkit and middleware service infrastructure to support Internet accessible laboratories and promote their sharing among schools and universities on a worldwide scale"*.

To the extent of our knowledge, the richest network of shared VRLs for control engineering education is UNILabs (see Table 2). UNILabs offers twenty-four labs in both virtual and remote modalities, being twelve of them specifically oriented to control engineering. At the moment, the UNILabs Consortium is composed of ten universities (nine from Spain, and one from Brazil). Nevertheless, membership is open to new institutions which desire to share their VRLs.

We strongly believe that the cross-institutional sharing of VRLs is essential to improve utilization levels, reduce shared costs, and allow access to a broader range of lab apparatus. In the near term future, we will witness the evolution of current VRL networks into *Networks of Networks* (NNs) that will support students accessing to a much bigger amount of VRLs. NNs are challenging because, despite their similarities, VRL deployment systems (see Section 3.3) have their own particularities that difficult their interconnection. As a matter of example, to operate VRLs in an interactive way, (a) users of iLab and UNILabs need to schedule labs in advance using a booking system, (b) the WebLab-Deusto scheduling system is mainly based on queuing, and (c) the Labshare Sahara scheduling system integrates both schemes: queuing and booking. Therefore, interconnecting those systems imply dealing with different scheduling schemes. To overcome this kind of problems, current research is being made on the creation of bridges between systems. In this line, Lowe et al. (2016) and Orduña, Bailey, DeLong, de Ipiña, and García-Zubía (2014) propose a bridge between iLab and Labshare Sahara, and a bridge between iLab and WebLab Deusto, respectively.

5.2. Enhancing lab interactivity

In 2008, Harward et al. (2008) distinguished three types of online experiments:

1. *Batched experiments*, where students fully specify the experiment in advance, and submit the specification as a request to the server. Thus, the specification is executed without any further intervention and the result is sent back to the student.
2. *Sensor experiments*, where students monitor or analyze real-time data streams without influencing the phenomena being measured.
3. *Interactive experiments*, where students control and monitor the experiment during its execution.

The majority of the VRLs are designed for interactive experiments. There are few labs oriented to batched (e.g., del Alamo et al., 2003) or sensor experiments (e.g. Amaratunga & Sudarshan, 2002), and most of them were developed more than a decade ago. Also, batched and sensor experiments do not really make sense in control systems applications and experiences, in which the need of a control loop implies some kind of interactivity. Moreover, the trend is advancing towards increasing interactivity levels. The following points outline some research that highlights such trend:

- *Handling VRLs via haptics*. Haptics are force sensitive devices able to remotely actuate real equipment or to interact with virtual reality models by returning feedback information from the reaction force to the action performed by the user (Quintas, Restivo, Rodrigues, & Santos, 2014). The introduction of Haptics into online experimentation can increase students attraction and interest. For instance,Santos and Carvalho (2013) describe a VL controlled with a haptic device for experimenting various forces of physics, such as the friction force, the aerodynamic force, or the gravitational force. Traditionally, haptics have been expensive. Nevertheless, research is being carried out to offer cheaper solutions. For example, Quintas, Restivo, and Ubaldo (2013) describe the construction of a low-cost force-feedback haptic device of 1 degree of freedom. With the open-source publication of the haptic designs and the cheapen of 3D printing, in a close future haptics may become a widespread technology to handle VRLs. Whether haptic devices can prove themselves useful for VRLs on control systems or not, is yet to be seen.
- *Gamifying VRLs*. The application of game principles into non-game contexts in order to improve user engagement, learning, evaluation, etc. is known as *gamification*. In the educational context, some gamification examples are *Supercharged!*[6] and *Robocode*,[7] which are games for understanding electromagnetic concepts and learning computer programming, respectively. In our opinion, gamification may play a key role in VRLs by introducing new features that leverage students' learning, such as dynamic visuals, curiosity, challenge, risk, etc. In this sense, it is worth mentioning Dziabenko and Garcia-Zubia's work (Dziabenko & Garcia-Zubia, 2011), where the effective merging of VRLs and online games is discussed.

5.3. Increasing control options

The main elements of a control loop, the *plant model* and the *controller*, have traditionally been strongly coupled in VRLs. For instance, Fig. 3 shows the virtual lab of a water tank described in Chacon, Guinaldo, Sanchez, and Dormido (2015). The lab includes a PI controller, and while users can configure its parameters, they could not change the controller itself. In labs with such monolithic architecture, students only can play with a reduced set of parameters to affect the system behavior or at most, they can choose between different pre-implemented controllers. From the VRL developers' point of view, this is an easy solution to implement. However, such limited configurability is not enough for postgraduate students, who need to design and test advanced control laws.

[3] http://www.nerela.kg.ac.rs/.
[4] http://www.go-lab-project.eu/.
[5] http://online-engineering.org/GOLC_about.php.
[6] http://web.mit.edu/mitstep/projects/supercharged.html.
[7] http://robocode.sourceforge.net/.

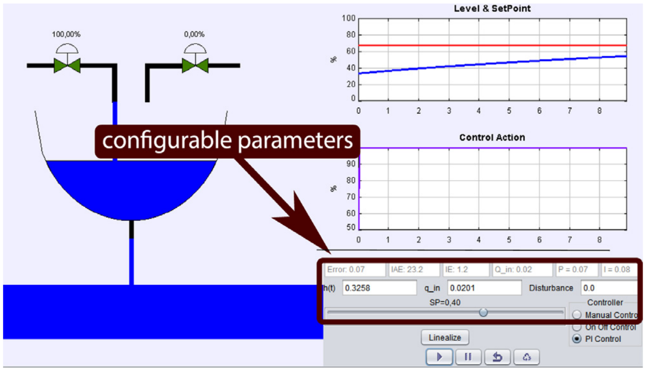


Fig. 3. Rigid virtual lab where the controller is configured via fixed parameters.

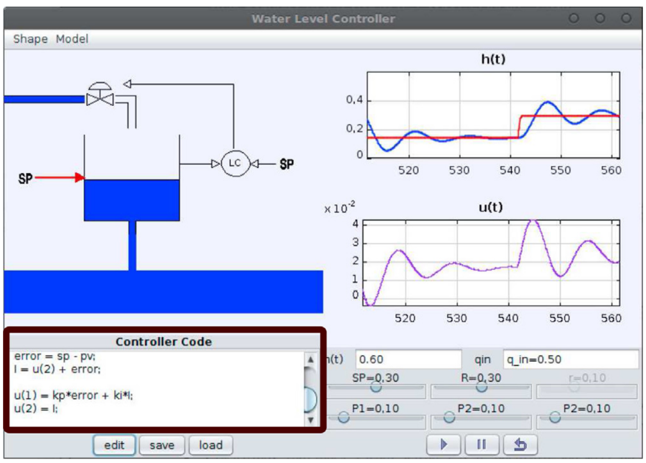


Fig. 4. Flexible virtual lab with an embedded programming language interpreter.

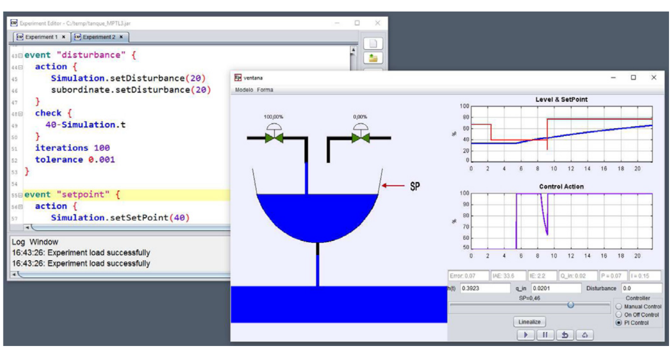


Fig. 5. Experiment editor where students can edit and run VRL controllers.

Recently, two approaches have been proposed to flexibilize VRLs by decoupling the controller from the plant model. Both approaches support students writing the code of the controller and running it without recompiling the VRL implementation:

1. Chacon et al. (2015) propose embedding programming language interpreters into VRLs. For instance, the virtual lab in Fig. 4 includes a text field where the student can write the controller implementation.
2. Galan, Heradio, de la Torre, Dormido, and Esquembre (2016) have developed a desktop application, named the *experiment editor*, where the student can load VRLs. Then, by using an interpreted language, the student can write experiments, or change the behavior of the lab by adding new functionality or re-implementing part of the lab. For instance, in Fig. 5 a liquid level control lab has been loaded into the experiment editor, which is then used to modify the lab behavior.

As Fig. 6 shows, once the controller has been decoupled from the plant, new possibilities appear for the client-server architecture. Although the plant is depicted with a real device, it could be a model as well (that is, the figure is valid for both virtual and remote labs). The controller can be placed either in the server or in the client side, as Figs. 6a and 6b represent, respectively. Traditionally, controllers have been placed in the same side as the plant in VRLs. However, it may be interesting to separate the controller and place it in the client side so that uncertain delays related to network communications appear in both sending the control action and receiving the feedback from the plant. Finally, as Fig. 6c shows, the controller can be placed not in the server or the client side, but elsewhere. In this case, the controller is provided as a service, which makes it reusable and allows interesting scenarios such as distributed control experiences.

The control loops which are closed through communication networks are becoming more and more frequent as the required hardware becomes cheaper and easier to access. A control system which communicates sensors and actuators through one or several communication networks is termed, in general, a real-time distributed control system. It is well known that communication networks introduce delays in the communication which are variable by nature, due to the band-width and the overload of the communication nodes. For this reason, the use of event-based control techniques (Beschi, Dormido, Sanchez, & Visioli, 2012; Guinaldo, Rubio, & Dormido, 2015) to avoid problems of instability in the process derived from the delays in the process/sensor/controller communication is a challenging research issue that can be connected with the implementation of the new generation of control remote labs.

To sum up, existing rigid labs only work for introductory courses. Advanced control students need more flexible approaches, as those summarized in this section. In our opinion, this trend of increasing control options for VRLs will continue in the future.

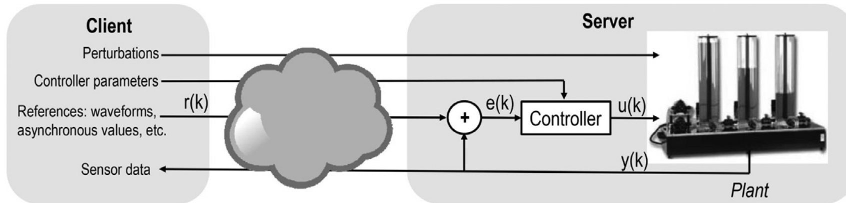
6. Conclusions

VRLs emerged about twenty years ago, being its use progressively spread across all educational levels: from primary schools to higher education, from vocational learning to universities, and from self-education to technical colleges.

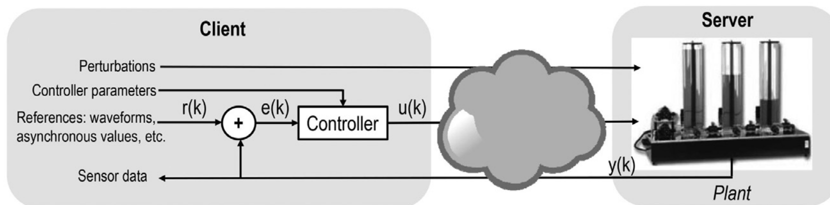
Teaching automatic control is challenging since it is a discipline with a very dynamic evolution and whose nature is cross-disciplinary. As Åström (1999), it is the hidden technology behind a wide range of applications, such as developing high-performance airplanes, fuel-efficient automobiles, industrial process plants, planetary rovers, communication networks, etc. VRLs fit particularly well into this scenario, since they enable opportunities without precedents for large-scale sharing of experimentation resources, and thus they can provide students with access to a wide variety of labs.

In this paper, we have tried to review the past and present application of VRLs in control education. Moreover, we have dared to look into the future to anticipate the evolution of this amazing technology that will bring lab experimentation to anyplace in the world.

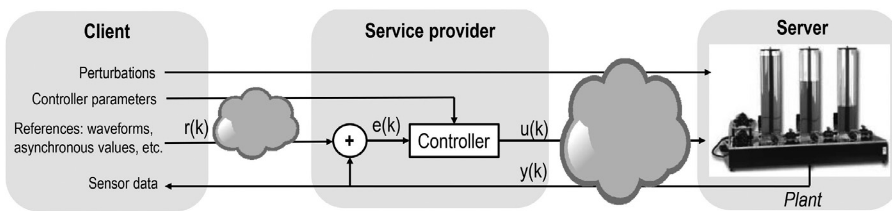
We have given a panoramic view of the main issues in the past eighteen years of developing and using VRLs for improving control engineering education. The use of up-to-date technological artifacts and the Internet as we notice it today may affect our actual vision on virtual and remote laboratories. But the final purpose of improving control education in the mid and long terms must be our driving force.



(a) Server-side controller



(b) Client-side controller



(c) Controller as a service

Fig. 6. Controller deployment options.

The set of tools available for the development of virtual laboratories is now very powerful for generating a wide range of simulations. From elementary simulations, to more elaborated virtual laboratories required in higher education. While Javascript is a flexible programming language and it is very well integrated with HTML and other W3C standards, there may still be a necessity for specific Javascript libraries to solve particular control problems or GUI tasks.

Regarding remote labs, we are witnessing a drastic price reduction of much of the hardware needed to build them. For instance, there exists a new generation of very cheap hardware and data acquisition equipment even for the modest pockets, such as Arduino, Raspberry Pi, RedPitaya and NI MyRio boards (to name a few), and the numerous cheap sensors and actuators that can be connected to them. Some of these boards also offer the possibility of establishing their own Web access point, so all that is needed to connect to them is a WiFi enabled device (that is, practically any computing device, including mobile ones).

In our opinion, thanks to the aforementioned technological factors, we are in a transition period from proof-of-concept VRLs towards mature and affordable online labs. Hopefully, in the close future, VRLs will become extremely popular in control education.

Acknowledgments

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